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ABSTRACT

Defining a "misconception" as an error of translation (transformation, correspondence, interpolation, interpretation) between two different kinds of information which causes students to have incorrect expectations, a Taxonomy of Errors has been developed to examine student misconceptions in an introductory biology course for science majors. Two forms of the Taxonomy are included. Major categories in the long form include: (1) primary encoding errors-missing and incorrect/faulty knowledge; (2) errors of relationship-missing and incorrect/faulty relationships; (3) errors of processing encoded information-algorithms missing, incorrect, or correct with an error; (4) errors of management, including failure to recognize or resolve conflicts or contradictions in knowledge, to generate effective "runnable" models, to develop effective and efficient metastrategies, and failure of confidence in using knowledge. Specific examples are presented to illustrate student misconceptions in terms of the Taxonomy. For example, when asked if a single base deletion in mRNA, tRNA, sense strand of DNA, nonsense strand of DNA, or both strands of DNA (both strands of DNA is the correct answer), 39 out of 72 students answered it incorrectly, suggesting missing knowledge. Examples of research studies are cited and potential inadequacies of the Taxonomy are discussed. (Author/JN)

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STUDENT MISCONCEPTIONS IN INTRODUCTORY BIOLOGY

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Introduction

There has been renewed interest in understanding human cognitive processes in realistically complex domains in recent years. One approach to the study of cognitive processes focuses on 'misconceptions' or 'preconceptions', especially those that seem to seriously interfere with student learning (e.g., Clement, 1982; Fredette and Lochhead, 1980; Clement, Lochhead, and Soloway, 1979; McCloskey, Caramazza, and Green, 1980; Pollatsek, 1981; Minstrell, 1981; McDermott, Piternick, and Rosenquist, 1980). Some misconceptions, referred to as 'conceptual primitives', are believed to be constructed by individuals over many years and to be highly resistant to change (Clement, 1982). Papert (1980) suggests, for example, that every child uniformly represents the world according to the ideas of Aristotle.

Fredette and Clement (1980) define a 'preconception' as a concept or idea which a student has upon entering a given topic in a course, and which has some consequence on the student's work in that particular area. They use the term 'misconception' for concepts or ideas which, from the point of view of the average professional, lead to unacceptable solutions or answers to questions and problems in the context of a course.

Another approach to the study of cognitive processes focuses on systematic errors that are observed in processing information, as in addition and subtraction of numbers (Brown and VanLehn, 1979). Brown and his colleages believe that systematic errors (bugs) arise from learner-generated repairs that are made when students, trying to solve a problem, find that they have missing elements or incompatible notions in

their mental frameworks (Brown and VanLehn, 1980; VanLehn, 1981a; VanLehn, 1981b).

Other researchers have concentrated on the organization of knowledge and its effects on the management of information in solving problems (Reif and Heller, 1981; Reif and Larkin, 1979; Schoenfeld, 1981). They find marked differences between the approaches used by novices and experts in solving problems. Still others (Norman, 1979) have traced the accretion of information as the learner moves to greater competence and command of a subject. Most of these studies have dealt with narrowly defined problems in fairly precise knowledge domains (such as mathematics, statistics, physics, algebra), with the researchers tending to concentrate on a single class of problems or a group of closely related problems.

In contrast, we became interested in examining student misconceptions in an introductory college biology course for science majors. Unlike the topics described above, biology consists largely of rather 'fuzzy' (poorly defined) concepts. During the past two academic quarters, we have reviewed student's performance on test questions, their comments in informal interviews, and their responses in formal interview settings. We found that the students' misunderstandings and confusions ranged all over the map. The boundaries of misconceptions appeared to be at least as fuzzy as the concepts themselves. In fact, we quickly realized that we weren't at all sure what a misconception was or how to differentiate it from other kinds of errors. The nomenclature in the literature seemed to be quite inadequate for the interpretation or prediction of the behaviours exhibited by biology students as they attempted

to explain biological structures and processes.

Taxonomy of Errors

This led us to develop a Taxonomy of Errors (Table 1). We don't know of any previous publication of a general taxonomy of errors, although there have been several notable attempts to classify intellectual processes (Bloom's taxonomy, 1959; Abercrombie, 1974; Bateson, 1980; Gray and Lochhead, Undated). Liebert and Thornton (1976) developed a handbook for problem-solving in biology which has some parallels to both Bloom's taxonomy and the taxonomy presented in this paper. All these taxonomies have some utility, yet are hampered by imprecision in both concepts and language. Our taxonomy is no exception.

The taxonomy described here has proved to be moderately useful to us, however, both in providing a perspective for viewing research in the field and for looking at errors of biology students. Thus, we present it in spite of our painful awareness of its inadequacies. The taxonomy no doubt exhibits many of the errors it professes to classify, including both overlapping and missing categories. We welcome your comments and suggestions.

A longer form of the taxonomy is presented in Table 2. We have not yet assessed whether the subcategories have practical utility. For example, it may be quite difficult to distinguish in I-A between (1) 'Never encoded' and (2) 'Encoded but not retrieved', or in I-B between (1) 'Incorrectly encoded in memory' and (2) 'Incorrectly retrieved from memory'. However, we have included them initially as potentially useful distinctions.

I-B, 'memorized but not understood', is a frequent problem in biology. Students often learn words with little understanding of their meaning. By 'understanding' we mean such things as the ability to define each word in a statement or relationship, to give an example of each word, to use/interpret each word in a novel statement, and to recognize instances of each word in non-verbal material (e.g., a picture or experiment). In general, depth of understanding is indicated by the ability to either generate novel material using one's knowledge or to solve novel problems. This concept is discussed in depth by Green, McCloskey, and Caramazza (1980).

Errors of relationship form a very large class (which might be more usefully categorized in another way - suggestions welcome!). The largest subset is (4), Errors of translation, involving the transition from one kind of information (e.g., verbal) to another (e.g., mathematical or visual). Errors of this type are very common in biology, where many new terms and concepts are introduced in a short span of time. This is also the area being most extensively studied in the field.

In fact, we now feel that we can offer a more precise definition of the term 'misconception' as it has been used by most researchers:

> A 'misconception' is an error of translation (transformation, correspondence, interpolation, interpretation) between two different kinds of information, that causes a student to have incorrect expectations. The kinds of information systems include, but are not limited to:
>
> words (in various languages);

tangible things (artifacts);

real world events (processes and phenomena);

non-verbal forms of notation;

mental constructs;

pictures (photos, drawings, charts, etc.); and

tangible models.

As noted earlier, students encounter deep-seated contradictions between the concepts being taught in introductory physics courses and the world-views that they have built on the bases of their experiences. There do not appear to be many such discrepancies between real-life experiences and the biology presented in our course (cell biology and population biology), however, presumably because students do not have much direct experience with cells and populations. Conflicts with intuitive expectations based on practical knowledge may be more common in courses concerned with reproduction, growth, disease, or other more familiar aspects of biology. On the other hand, biology may simply be less counter-intuitive than physics even in the most familiar topical areas, because of the limited visual and/or neuromuscular experiences students have with biological events. For example, we are generally aware that plants grow, but we don't really 'see' them doing it. We know a baby develops in the womb, but even the expectant mother has very little direct experience with the processes involved. Biological processes are surprisingly invisible.

Procedural errors are not readily identified in the setting

described here. This may reflect the relatively minor role of quantitative problem solving in introductory biology, and/or the difficulty of separating procedural problems from those of knowledge acquisition. Errors in the management of knowledge are, in contrast, very common. Biology students must master many new terms and concepts, all of which are inter-related with respect to both structure and function. It is difficult enough for students to grasp the central ideas presented to them in the short space of time available. It is even more challenging for them to begin to perceive the major relationships (The observed difficulties lend support to the European notion that each subject should be taught over a period of several years so that the structure of the subject matter can be assimilated intuitively at first, and then with increasing levels of detail and rigor - Wirszup, 1979).

The development of confidence in using acquired knowledge is equally problematic for biology students. This area has not yet received much attention from cognitive scientists, although it is not being totally ignored.

Examples

Some current research in the field is classified according to the Taxonomy of Errors in Table III. To further illustrate the way in which we perceive the various categories, some findings from biology are described below. The difficulties we have in classifying problems reveal both the complexity of the situation and the inadequacies of the taxonomy.

The following question appears to represent Missing Knowledge.

Thirty-nine of 72 students answered it incorrectly:

Which has more serious consequences for a cell, a single base deletion in:

A. a mRNA molecule;

B. a tRNA molecule;

C. the sense strand of DNA;

D. the nonsense strand of DNA;

E. both strands of DNA?

(correct answer - E)

Missing knowledge is probably the least interesting category of errors, although it is useful in informing the instructor what concepts have not been adequately presented. In this case, students apparently did not fully appreciate the value of redundant information in DNA and the possibilities for repair, even though this idea had been mentioned several times in the instructional materials (the details of the repair process itself had not been examined). Students incorrectly concluded that a deletion in the sense strand of DNA was more critical than deletions in both strands.

The next question reveals erroneous knowledge in some students and a pronounced absence of misconceptions in others. Students were asked to explain what is meant by the term "test tube baby", referring to a technique developed in England a few years ago and often mentioned in newspapers and magazines. The term had not been discussed in class. Of

67 students, 54 (82%) answered essentially correctly. Considering how hard the press has worked to sensationalize the technique indicated by this term, it is perhaps surprising that so few students harbored 'misconceptions'. The misunderstandings that were revealed are quite interesting: one student believed that electric shock is required to unite the sperm and egg; two students thought that chromosomes could be added or removed in vitro; and eight students believed that the baby develops to term in the artificial environment (one foreign student had never heard of the term). We suspect that, where they do exist, these misunderstandings could be easily corrected by instruction. Since students don't experience these processes directly (as in physics), we believe they are more willing and able to relinquish their ideas about the how the processes occur - - unless those ideas are tied to a powerful dogma in the student's life (such as religion).

Biology offers many examples of errors of management of knowledge. Students seem to experience considerable difficulty in following a chain of logic. The following question provides a classic example of this problem. Forty-nine of 72 students were unable to answer it correctly:

Which of the following are products of translation?

A. tRNA's;

B. amino acids;

C. activating enzymes;

D. mRNA's;

E. all of the above.

(correct answer - C)

This is an interesting item which one of us (Fisher) has used nearly every quarter for about six years in teaching introductory genetics and introductory biology. The item was created by Dr. Richard Snow of the Genetics Department at the University of California - Davis. Despite the fact that the question is generally available to students on previous exams on file in the library, about 50% get it wrong every quarter. Yet when you talk with students, you generally find that they know the three essential pieces of information: translation produces proteins; enzymes are proteins; activating enzymes are enzymes. The most frequently selected wrong answer is amino acids, because, they reason, translation produces a chain of amino acids (they often tell you, too, that something is wrong with the question, because it is more correct to call amino acids building blocks than products!).

Clearly, something inhibits them from following this line of reasoning: If translation produces proteins, and enzymes are proteins, then translation produces enzymes. And, if activating enzymes are enzymes,

and translation produces enzymes, then translation produces activating enzymes. Is it a problem of moving from a general class (polypeptide chains, proteins) to specific examples (activating enzymes)? Is it because they become so involved in their mental models of the complex translation process that they can't see the end product clearly? The explanation is not readily apparent.

The next question is difficult to classify because it incorporates the potential for many different kinds of errors, and the multiple choice format does not reveal which ones or how many are actually involved. Thirty-six of 76 students answered it incorrectly:

> Complementary DNA strands can be separated ("melted") by gentle heating. The amount of heat required is directly proportional to the number of hydrogen bonds between the two DNA strands. Based on your knowledge of DNA structure, which DNA helix below would require the most heat? (Assume all strands are identical in length and fully complementary.)
>
> A. poly-A (a polymer composed of adenine nucleotides) paired with poly-T;
>
> B. poly-C paired with poly-G;
>
> C. poly-AT (a polymer composed of alternating adenine and thymine nucleotides) paired with poly-TA;
>
> D. a random polymer containing all four bases (C,G,T,A)

paired with a complementary strand that also contains

all four bases.

(correct answer - B)

It appears that most of the students who answer this item incorrectly know the facts that are necessary to answer the question: namely, that cytidine (C) and guanine (G) pair with three hydrogen bonds and that adenine (A) and thymine (T) pair with two hydrogen bonds. The maximum number of hydrogen bonds, then, would be obtained with a maximum number of C-G base pairs (answer B).

Why can't students select the correct answer? Do they think of these particular facts when they read the problem? (That is, do they retrieve this information from memory?) If so, do they recognize the relevance of these facts to the problem? (That is, do they perceive the relationship?) Do students have difficulty generating a mental image of the DNA strands from the verbal description (translation)? Do they have trouble deciding whether there are more bonds in poly A-T or poly G-C, a procedural (mathematical) skill? Or do students panic because of the applied nature of the question, and simply assume that they don't know enough to answer it (confidence)? More work is required to determine what may be the major sources of difficulty.

An example of a 'crisis of confidence' comes from an interview done with a student, S, who was in the top third of the class. Some of the changes associated with differentiation and development were described, and S was asked to suggest ways in which cellular regulation might account for the changes. S was unable to do so. The interviewers then

asked S to describe the chemiosmotic theory, to discuss the role of gradients in the cell, to describe induction and repression of bacterial operons, to explain feedback inhibition of enzymes, and to discuss the function of allosteric molecules in general. S was able to respond to all of these requests correctly and in some detail. S was then admonished to let the imagination roam, to feel free to make educated guesses, and not to be concerned with whether or not something actually happens - but just to consider possibilities. With this encouragement, S was then asked to draw on the material that had just been discussed and suggest some possible control mechanisms for differentiation. S was unable (or unwilling) to suggest any mechanisms. Does this problem simply require more risk-taking than students are accustomed to, to hypothesize rather than accept and memorize the given? Or are there other explanations?

Another example of a crisis of confidence involved a test question on meiosis. Students were given a sequence of eight photographs illustrating the major stages of meiosis in a plant, and a corollary set of eight diagrams illustrating meiosis in an animal. Both sequences were obtained from Biological Sciences by Keeton. The students were asked whether the DNA content of the cell in the first photograph and diagram (prophase I) was:

1N (haploid);

2N (diploid); or

4N (diploid and replicated).

(correct answer - 4N)

More than half the students answered incorrectly (and this item had been previously judged to be among the easiest questions on the test!). Yet most students had the pieces of knowledge required to answer correctly. They could recite the cell cycle (G1, synthesis, G2, and meiosis) and knew that DNA replication occurred at the synthesis stage. They recognized that the series of pictures and diagrams represented meiosis and that the first image was prophase I. Students also knew that a cell must be diploid to undergo meiosis, and that its DNA must be replicated before cell division can begin. Yet they chose 1N or 2N rather than 4N, because they could not see the sister chromatids in the diagram. This one visual clue over-rode all of their 'knowledge' of biology.

Summary

There are several interesting directions we expect to follow in our subsequent research. These include:

- continued assessment of errors made by students in introductory biology for science majors, using interview and other techniques,
- use of a computer system for frequent individualized testing to assess student performance on multiple choice and numeric answer items,

- refinement of the Taxonomy of Errors,

- examination of non-science majors to determine if this population has different kinds of misconceptions or misunderstandings, and

- examination of young children to detect conceptual primitives concerning biology.

We also hope to explore the following hypothesis. It appears that children begin life with many 'conceptual primitives'. When they find out that their ideas are erroneous, they sometimes accommodate the contradictions without resolving them, and they sometimes succeed in changing their ideas.

In certain instances, however, we suspect that individuals find it too difficult to make the transition from the old mental framework to the new one, and too stressful to accommodate both, so they give up entirely. These people would have what we think of as 'mental blocks', and they would tend to avoid the subject causing the problem (mathematics or biology or physics or whatever) like the plague. The subject just appears to be incomprehensible to them. It is as if the subjects deploy a management strategy of conservation, to avoid taxing themselves, much as we are able to turn our minds off to the knowledge of impending disaster (such as an earthquake or landslide). Is this an accurate representation? What factors influence the decision? These are some of the questions of interest to us.

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TABLE 1

TAXONOMY OF ERRORS

(short form)

I. Primary Encoding Errors: Declarative Knowledge

   A. Missing knowledge

   B. Incorrect or faulty knowledge

II. Errors of Relationship: Declarative Knowledge (Procedural?)

   A. Missing Relationships

   B. Incorrect or faulty relationships

      1. Errors of contradiction
      2. Errors of scale
      3. Errors of analogy
      4. Errors of translation (Misconceptions)

III. Errors of Processing Encoded Information: Procedural

   A. Algorithms are missing

   B. Algorithms are incorrect (bugs)

   C. Algorithms are correct but a mistake is made (a slip)

IV. Errors of Management: Executive Knowledge

   A. Failure to recognize conflicts or contradictions in knowledge

   B. Failure to resolve conflicts or contradictions in knowledge

   C. Failure to generate effective, runnable models

   D. Failure to develop effective metastrategies

V. Lack of Confidence in Using Knowledge: Emotive

TABLE 2

TAXONOMY OF ERRORS

(long form)

I. Primary Encoding Errors: Declarative Knowledge

A. Missing knowledge

1. Never encoded (learned)
2. Encoded but not retrieved

B. Incorrect or faulty knowledge

1. Incorrectly encoded in memory
2. Incorrectly retrieved from memory
3. Memorized but not understood

II. Errors of Relationship: Declarative Knowledge (Procedural?)

A. Missing relationships

1. Temporal
2. Spatial
3. Conceptual

B. Incorrect or faulty relationships

1. Errors of contradiction
2. Errors of scale
3. Errors of analogy
4. Errors of translation (transformation, interpolation, correspondance, interpretation) between items in different domains such as, but not limited to:

   a. Verbal symbols (words - various languages)
   b. Other forms of notation (e.g., AaBb)
   c. Tangible items (e.g., microscope, cat)
   d. Real world situations (observable phenomena, experiences)
   e. Pictures (diagrams, drawings, photographs, charts)
   f. Constructs (e.g., chemiosmotic theory)
   g. Models

TABLE 2, continued

III. Errors of Processing Encoded Information: Procedural Knowledge

A. Algorithms are missing

B. Algorithms are incorrect

C. Algorithms are correct but a mistake is made.

IV. Errors of Management: Executive Knowledge

A. Failure to recognize conflicts or contradictions in knowledge

1. Failure to distinguish between relevant and irrelevant information, or major and minor effects
2. Failure to perceive competing, conflicting, additive, or other pertinent relationships in a domain of knowledge

B. Failure to resolve conflicts or contradictions in knowledge

1. Failure to verify new knowledge (i.e., to integrate new knowledge with preexisting knowledge)
2. Incorrect verification of new knowledge
3. Failure to 'know' things in more than one way (to use redundant knowledge)

C. Failure to generate effective, 'runnable' models

1. Failure to try to generate a runnable model
2. Generation of an incomplete model
3. Model is generated but erroneous properties are assigned to elements in model

D. Failure to develop effective & efficient metastrategies

1. Failure to develop useful heirarchies
2. Inability to move through (down, across) a chain of relationships, even when the relevant pairwise relationships have been learned)
3. Incorrect organization
4. Missing organization

V. Failure of confidence in using knowledge

TABLE 3
SOME EXAMPLES OF RESEARCH IN EACH CATEGORY

I. Primary Encoding Errors

Norman (1978)

II. Errors of Relationship

Minstrell (1981)
Pollatsek (1981)
Champagne & Klopfer (1981)
McDermott, Piternick, & Rosenquist (1980)
Lochhead (1980)
Clement (1982)
Gray & Lochhead
Fredette & Lochhead (1980)
Fredette & Clement (1980)
McCloskey, Carramazza, & Green (1980)
Caramazza, McCloskey, & Green (1981)
Clement, Lochhead, & Monk (1979)
Clement, Lochhead, & Soloway (1979)
Lesh (1981)
Lesh, Landau, & Hamilton (1981)

III. Errors of Processing Encoded Information

Brown & VanLehn (1979)
Brown & VanLehn (1980)
VanLehn (1981a & b)

IV. Errors of Management of Knowledge

Reif & Larkin (1979)
Reif & Heller (1981)
Schoenfield (1981)

V. Lack of confidence in using knowledge